Comparison of Temporal Rainfall Distributions for Near Probable Maximum Precipitation Storm Events for Dam Design

James N Moore, P. E., Civil Engineer and
Ray C Riley, P. E., Watershed Planning Specialist
National Water Management Center, NRCS
Little Rock, Arkansas

Abstract

The Natural Resources Conservation Service (NRCS) has assisted local sponsors with analysis, design and construction of approximately 26,000 of the 80,000 dams in the National Inventory of Dams. Many of these dams are reaching their design life and require rehabilitation. Rehabilitation efforts come at a time when NRCS is in the process of evaluating a potential change from a minimum 6-hour storm duration design criteria east of the 105th principal meridian to either 24-hour duration criteria or a multiple duration criteria. The change in long standing NRCS criteria results from a number of both internal and external considerations, which will be enumerated in this paper. This paper will focus on the 24-hour duration but the same procedures and process presented may also be used for storm duration other than 24-hours.

This paper will evaluate current and proposed NRCS precipitation distributions as well as other distributions that are considered appropriate for use with 24-hour Probable Maximum Precipitation (PMP) events. Potential 24-hour rainfall distributions were narrowed to four distributions through preliminary screening, which will be evaluated in greater detail. These four distributions are: 1) The 24-hour version of the NRCS standard emergency spillway and freeboard hydrograph (ESFB) rainfall distribution, 2) The five-point PMP distribution, 3) The critically stacked 24-hour PMP distribution and 4) The temporal rainfall distribution based on the maximum rainfalls recorded on world scale. The merits and deficiencies of each procedure will be evaluated.

The importance of the period of maximum intensity (i.e. maximum 1-hour) and its placement within each distribution will be evaluated. A data set of seventy-two (72) NRCS Floodwater Retarding Structures will be evaluated using 24-hour duration PMP or near PMP rainfall. The spillway flow depths of the four distribution patterns are compared to the current NRCS 6-hour duration design for comparative purposes. The NRCS SITES computer model was used to determine the spillway flow depths for each scenario.

Introduction

Since 1944, the Natural Resources Conservation Service (NRCS) has assisted local sponsors with analysis, design and construction of approximately 26,000 of the 80,000 dams in the National Inventory of Dams throughout the United States. Many of these dams are nearing their design life and require rehabilitation. This comes at a time when NRCS is considering a change in the design criteria for floodwater retarding structures. NRCS is considering a change from a minimum 6-hour design criteria to either 24-hour duration criteria or multiple duration criteria for structures east of the 105th principal meridian. The change in long standing NRCS criteria results from a number of both internal and external considerations. Some of the considerations for the change are:

- Storm data for 24-hour periods is the most readily available historical precipitation data.
- The 24-hour storm is the most widely used flood event for water management planning and design.
- Many state agencies require 24-hour hydrologic design criteria for dams.
- NRCS has documented auxiliary spillway failures due to longer duration flows that exceed current NRCS minimum 6-hour design criteria.
- For large watersheds with a long time-of-concentration, the storm duration should exceed the time-of-concentration to achieve maximum hydrological response.

With the potential for NRCS to adopt 24-hour Probable Maximum Precipitation (PMP) as design criteria for high hazard dams, the question remains as to which rainfall distribution is the most applicable to 24-hour PMP designs. The merits and deficiencies of various distributions will be evaluated. A critically stacked distribution based on world record rainfall volumes could be used for the design of high hazard dams.

Rainfall Distributions

Background

Currently, NRCS uses standard synthetic 24-hour rainfall distributions identified as Type I, Type IA, Type II and Type III. These distributions are used for evaluation studies (Flood Insurance Studies, Flood Plain Management studies, flood routings, urban damage evaluations, etc.) as related to evaluation of 24-hour events (i.e. 1-year generally up through 500-year events). These four distributions were developed for various regions of the country, e.g. Type II is associated with a Midwestern type thunderstorm. These distributions work well in the regions where they were intended and for frequencies up through the 100-year and 500-year events typically analyzed in flood series evaluations. This is not surprising since this is the purpose and the regions for which the patterns were developed. This paper is limited to the areas east of the 105th meridian where only the Type II and Type III distributions are applicable. In addition to the Type I, IA, II and III distributions, the NRCS utilizes a standard emergency spillway and freeboard hydrograph (ESFB) design hydrograph rainfall distribution in making determination and analysis of auxiliary spillway flow depth and duration.

The precipitation patterns discussed above were developed from historical records that were almost entirely from events with recurrence intervals less than 100 years. The basic data is heavily concentrated in the four-inch to ten-inch total rainfall range. All of the patterns work well when used in the region and range of rainfall totals for which they were developed. The same patterns may not be appropriate for PMP size events.

Other distributions east of the 105th meridian can be developed following procedures in National Oceanic Atmospheric Administration Hydrometeorological Report 52 (HMR-52). HMR-52 used Hydrometeorological Report 51 (HMR-51) to determine the 6-hour and 12-hour PMP rainfalls. Rainfall amounts for 2-hour and 3-hour durations were obtained for the

100-year recurrence interval from Weather Bureau Technical Paper No. 40. For shorter durations, 100-year rainfall amounts were determined from NOAA Technical Memorandum NWS 35. The rainfalls were expressed as a percent of 6-hour 10 square mile PMP and a set of smooth curves developed for HMR-52. The curves were used to determine the ratios of the one-hour point rainfall to 6-hour 10 square mile rainfall.

There is a large volume of information related to PMP (partial PMP or near-PMP) and the meteorological circumstances that are necessary to support PMP. As a starting point, the basic information used in the development of PMP is contained in NOAA Publication HMR-51. Many of the events used in the study approached PMP status. Among the events, Alvin, Texas and Smethport, Pennsylvania obtained more than 89% and 93%, respectively, of the predicted 24-hour PMP precipitation totals for their locations. In addition, Yankeetown, Florida and Thrall, Texas had 77% and 80% of the predicted 24-hour PMP precipitation totals for their respective locations in 18 hours. In each of these cases, changes in meteorological conditions in the last six hours caused each of these locations to fall short of the predicted 24-hour PMP. Typical changes in meteorological conditions contributing to storm dissipation include, but not limited to, loss of energy, lack of renewable moisture (storm inflow), frontal movement, internal atmospheric cooling, or diurnal atmospheric cooling. Several sites exhibited six to twelve hours of near PMP rainfall but in each case were unable to maintain PMP conditions for a full 24 hours. Some notable locations in this group include Hale, Colorado; Boyden, Iowa; Ewan, New Jersey; Cheyenne, Oklahoma; Hallet, Oklahoma and Tyro, Virginia which had 71%, 67%, 65%, 58%, 62% and 69% of the predicted 24-hour PMP respectively.

Since the 1930's, spillway requirements for most reservoirs in the United States have been based on the PMP developed by NOAA. PMP is used to calculate the probable maximum flood. Technical Paper 40 (1961) was developed for the Soil Conservation Service by the Weather Bureau, U. S. Department of Commerce and included the 6-hour PMP. This publication was followed by Hydrometeorological Report 51 (HMR-51, 1978), which was developed for the Corps of Engineers by the National Weather Service, U. S. Department of Commerce, National Oceanic and Atmospheric Administration Service. Agency and Bureau names have undergone several changes since 1960. For the sake of simplicity, the current NOAA identification will be used for the remainder of this paper.

Rainfall Data

The maximum rainfall volume-duration information for the United States is located at the following web address:

www.nws.noaa.gov/oh/hdsc/max_precip/max_precip.htm

The web site also contains information for maximum observed volume-duration information worldwide (Figure 1 and Table 1). Technically, the values on the curve are the maximum volumes measured over a specific time period (duration). The average intensity (inches/hour) for any duration interval can be obtained by dividing the volume in inches by the duration in hours. For one-hour duration, we are dividing the measured valued by one. Therefore, the one-hour volume-duration value on the World Curve is also an one-hour intensity value.

A best-fit line through the World Record values is a **"World Record Volume-Duration Curve"**. Even though the volume-duration values on Figure 1 essentially plot as a straight line on a Log-Log scale, the relationship is curvilinear. A curve can be developed parallel to the best-fit line to essentially envelop the World Record rainfalls. An envelope curve of maximum volume-duration events that have been observed worldwide is shown on Figure 1. For simplicity, this envelope curve will be referred to as the **"World Curve"** for the remainder of this paper and represents nearly full scale meteorological factors involved in a PMP event (i.e. moisture, energy, duration). While the accuracy of measurement for any point on the curve can likely be questioned, there are numerous other second and third order volumes that are comparable. Eliminating the maximum value and substituting a second or third order volume on the World Curve does not significantly change the curve. For example, if you find a reason to eliminate the 71.85 inches in 24-hours at Foc Foc on Reunion Island in January 1966, you can substitute the 68.82 inches in 24-hours measured in Taiwan on July 31-August 1, 1996 (Typhoon Herb).

The largest one-hour precipitation ever noted historically was 15.78 inches in Shangdi, China on July 3, 1975. The United States maximum observed in semi-tropical Kilauea, Kauai Hawaii was 12.00 inches in one-hour. Considerably less than 12.00 inches in one-hour as a maximum intensity for most of the continental United States could reasonably be expected.

The World Curve has a high correlation and continuity in magnitude from duration to duration. The notable absence of any significant outliers above the curve gives a strong indication that the World Curve does represent a physical upper limit to volume-duration values based on the current world climate. One outlier at the 10-hour duration is 11% greater than the envelope curve. The implication is that there are definite physical and meteorological upper limits for any specific duration that have not been exceeded on a global scale. The World Curve appears to be a definite envelope curve that reflects current global climatic conditions. Based on the curve, it appears that there are physical and meteorological upper limits on a global scale, and similar, but lower, upper limits for any specific location or region.

The maximum one-hour value is more significant than the two-hour or three-hour maximum value. The number of occurrences of maximum intensity rainfall events begins to decline very rapidly for durations in excess of one-hour. Quite simply, optimum conditions become more and more difficult to maintain as duration increases. There should be more near maximum intensity one-hour events and progressively fewer large volume-duration events as the duration increases. If optimum conditions could be maintained for extended periods, the maximum two-hour value would be twice the one-hour value. Even on the World Curve, the two-hour maximum of 22.6 inches is only 40 percent greater than the maximum one-hour value of 16.2 inches. The maximum one-hour and the maximum two-hour events for any region almost always occur in separate events. In many historical rainfalls, the percentage increase in the two-hour over the one-hour is much less than 40 percent. A logical conclusion from a design perspective is that it is very important to get the maximum one-hour intensity value as nearly correct as possible. The second hour is not nearly as important because the optimum conditions diminish.

The maximum one-hour data set was provided by the NRCS National Water and Climate Center (NWCC). The maximum one-hour values for each state have been individually verified.

The data set from the NWCC was developed and verified based primarily on 30-minute data with the inclusion of 15-minute data where available. The subject hourly data set minimizes a problem with published hourly precipitation data. The published hourly precipitation data is normally reported on clock-hours. As an example of the difference that this can make, the maximum one-hour clock value was 6.45 inches between 6 p.m. and 7 p.m. The 30-minute data showed that 6.92 inches fell in a one-hour period between 5:30 p.m. and 6:30 p.m. The shorter the time increment, the greater the accuracy and magnitude of the resultant data. The maximum recorded value from the NWCC database is given for each state in Table 2. Iowa one-hour recorded rainfall of 8.0 inches was the highest in the study area. Iowa second highest rainfall of 6.6 inches has a higher correlation to the highest one-hour rainfall of the surrounding states.

While two-hour and three-hour maximum volumes would be helpful in verifying some of the information presented later in this report, extracting these values would be a time consuming project. The NOAA network has not yet defined the two-hour and three-hour volume-durations as well as it has defined the one-hour data. The one-hour volume-duration (intensity) is by far the most critical of the short duration values and was the easiest to extract.

NRCS Standard Type II and Type III Distributions

The NRCS Type II and Type III patterns are very similar. The Type II pattern distributes 45 percent of the total 24-hour rainfall in the maximum one-hour while the Type III pattern distributes 40 percent of the total rainfall in the maximum one-hour. Maximum intensities (the maximum one-hour and two-hour) and where they are placed in the 24-hour arrangement tend to govern the hydrologic design so it is critical to develop the correct distribution with the correct maximum intensities. For a 100-year rainfall event of 8.0 inches, 40 to 45 percent (3.2 to 3.6 inches) occurring in a peak one-hour is totally reasonable. When the same patterns are applied to a 24-hour PMP event of 40 inches, the peak one-hour rainfall becomes 18 and 16 inches respectively for the Type II and Type III patterns. For the area east of the 105th meridian, the Type II and Type III patterns used with 24-hour PMP values consistently produced one-hour and two-hour intensities that far exceeded any known or documented rates. Because the Type II and Type III distributions over-predicted the maximum one-hour intensity for PMP events, they were excluded from further study. While it might initially be expected that higher hourly intensities than historically observed could occur during PMP events, there is also evidence that maximum intensities are limited by local physical and meteorological restrictions. A case can be made that maximum or near maximum intensities for short durations (i.e. one-hour) have already been observed in many states and regions.

NRCS Standard Emergency Spillway and Freeboard (ESFB) Distribution

The dimensionless conversion of the ESFB distribution from a 6-hour to a 24-hour pattern has been used with PMP events in a number of states where 24-hour storms are required as a part of the State's dam safety criteria and approval process. Therefore, it seemed reasonable that this pattern should also be considered and tested. The ESFB pattern distributes 19 percent of the 24-hour rainfall in the maximum one-hour and 35 percent of the total volume in the maximum two hours. For a 40-inch 24-hour PMP event, the maximum one-hour intensity would be 7.6 inches. This seems to bring the maximum intensity in line with historical experience with known extreme events around the country. The World Curve distributes 22 percent of the 24-hour rainfall in the maximum one-hour and 30 percent of the total volume in the maximum two hours. Although the ESFB distribution and the World Curve distribution were developed from entirely independent data sources, the distributions are similar when compared on a volume-duration basis. The world curve supports the ESFB.

HMR-52 Distribution

For the area east of the 105th meridian, 24-hour PMP rainfall totals range from 24 inches in the northern climates to 47 inches in the Florida and Gulf Coast regions. Federal agencies, including NRCS, have not attempted to develop a rainfall distribution pattern (or patterns) related directly to Probable Maximum Precipitation. Some federal agencies have used a "critically stacked pattern" based on procedures in HMR-52 and published PMP intensity-duration data. This yields a significantly different distribution than actual distributions associated with PMP or near PMP size events. With a critically stacked pattern, the one-hour PMP is imbedded in the six-hour PMP, which is in turn imbedded in the 24-hour PMP. This procedure is chosen because it represents a worst-case design scenario.

5-Point Distribution

An additional proposed distribution utilizes the PMP rainfall from the HMR-51 and develops a mass curve of five points. This method will be referenced as the 5-point distribution. This method divides the 24-hour distribution in to four quadrants. The 6-hour PMP is placed in the second quadrant. The rainfall difference of the 12-hour PMP and the 6-hour PMP is placed in the third quadrant. The remaining rainfall for the 24-hour PMP is divided in the first and fourth quadrant. A uniform distribution is utilized for each six-hour increment.

World Curve Distribution

The values on the World Curve are volumes (inches) over a given time period (duration). Average intensity at any point on the World Curve can be determined by dividing the volume at any point on the curve by the corresponding duration to obtain the average intensity in inches per hour. For one-hour duration, average intensity and volume-duration are the same number since we are dividing by a value of one. If the World Curve does actually represent the upper limit of expected volume-duration under current climatic conditions, the implications for evaluating PMP at other locations is tremendous. There is minimal difference between a best-fit curve and a true envelope curve. The curves are close together and percentages determined for each duration would be identical as long as the two lines are parallel. Based on physical constraints associated with even accurately measuring such large intensity events, it can be concluded that the best-fit curve is the appropriate curve. A first-order curve fit through the World Record Volume-Duration data gives a correlation (R^2) value of 0.9988. The first-order curve was used to develop a parallel envelope World Curve.

The world record 24-hour precipitation is 71.85 inches (Figure 1 and Table 1). The envelope of World Curve data gives 75 inches of precipitation in 24 hours. Any number of temporal distributions can be developed to get from 0 to 75 inches in 24 hours. The lower limit of possible distribution patterns would be defined by a constant rate of 3.125 inches per hour for

24 hours. A uniform distribution represents a minimum potential design condition for the subject volume. For design purposes, we certainly want to use a distribution that is more restrictive than a uniform distribution. The other extreme and the most conservative procedure would be to encompass all maximum volume-duration values within the 24-hour distribution. The result would be a critically stacked distribution. This is most assuredly a conservative distribution since there is no indication that all maximum volume-duration values have or ever will actually occur during any single event. In fact, in the world record data base, no single event represents the maximum volume-duration value for more than two durations until we get to durations of 18 hours and longer. If we accept the validity of the World Curve, this represents a design distribution that would not be expected to be exceeded for any duration.

Of all the major factors that affect maximum volume-duration values, the only one that has a likelihood of changing in the next few centuries is global temperature. Orographic and local topographic influences are unlikely to change to any appreciable extent. Distances from large water bodies will not change appreciably for most locations although mean sea level elevations around the world could rise. Temperature together with the size and proximity to large water bodies show the most potential for changes that might be measured in terms of centuries. If global warming is a true phenomenon, we should begin to see a number of new World Record Volume-Duration values slightly above the current curve. The long-term consequence would be a new curve parallel to the current curve with slightly higher values. A one to two degree change in global temperatures would be sufficient to produce dramatic changes along the world's coastlines. The increase in maximum volume–duration values would be small but the frequency of occurrence of near PMP size events could increase.

The natural continuity from one volume-duration to the next volume-duration of the world curve is ideal for developing a distribution curve. The fact that the curve envelopes the historical World record rainfall value for that duration makes it more desirable. Developing a 24-hour (or any other duration) rainfall distribution pattern from volume-duration data requires two basic steps. First, one needs to know the percentage of the total 24-hour storm volume that occurs for each duration (1, 2, 3, 6-hours etc). The second more subjective part of a rainfall distribution pattern is to determine the time within the 24-hour period in which the most intense period of rainfall is most likely to occur. Using the World Curve, the two-hour maximum is 40 percent greater than the maximum one-hour value and the three-hour value is 22 percent greater than the two-hour value.

A distribution curve defines the percentage of total precipitation volume that occurs for a period of time. In the development of a 24-hour distribution curve from the World Curve, each shorter volume-duration is divided by the 24-hour maximum volume-duration value. A critically stacked distribution pattern can be created by including the maximum one-hour value within the maximum two-hour value and the maximum two-hour value within the maximum three-hour value, etc. For this paper, the distribution was developed based on three-hour increments after the 6^{th} hour. The end result is a 24-hour critically stacked volume-duration distribution based on the World Curve values. The process of converting volume-duration data to a rainfall distribution is discussed later in this paper.

The percentage for the maximum one--hour rainfall from the 24-hour World Curve Distribution is greater than the current rainfall percentage of the 24-hour ESFB pattern for the maximum one-hour. For all other durations, the rainfall percentages for the 24-hour World Curve Distribution are less than the rainfall percentages for 24-hour ESFB pattern. The World Curve is a critically stacked pattern that should not be exceeded for any regional distribution that essentially parallels the World Curve distribution. Overall, the two curves are remarkably similar considering that they were developed from two entirely different sources. The overwhelming difference is that the 24-hour World Curve was developed from PMP size events while the 24-hour ESFB distribution was developed from four to ten inch size events and then extrapolated to larger events. It would seem logical to use the World Curve distribution for PMP size events. The areas of the US where this distribution applies will be discussed in a companion paper.

Placement of the Most Intense Period of Rainfall Within the Distribution

The placement of the most intense period of rainfall is the most important decision in the development of a critically stacked rainfall distribution. Based on physical process, the maximum intensity usually occurs during the first part of a distribution where optimum conditions can most readily be maintained. Optimum conditions will gradually decrease due to limited energy, moisture, frontal movement or change in other meteorological conditions that will ultimately limit or terminate the storm. In exceedingly rare instances, the storm may hold together for up to 24-hours. The occurrence of the maximum one-hour within the first six hours is strongly supported by an examination of the historical storms in HMR-51 and by all recent near PMP storms with the exception of the 1979 storm in Alvin, Texas. Most historical data seems to indicate that maximum intensities are achieved very early in the storm and then begin to decay after the one-hour maximum intensity. All of the historical events in the HMR-51 had greatest rainfall amounts in the first six hours of the storm. Remember that the maximum two-hour intensity is only 40 percent greater than the maximum one-hour value in the world curve data.

The SITES program assists the engineer in the hydraulic and hydrologic analyses of dams. The program develops inflow hydrographs and uses the storage-discharge relationships at dam sites to flood route hydrographs through existing or potential reservoirs. NRCS and the Agricultural Research Service (ARS) jointly developed the earth spillway erosion technology incorporated in the program to enhance the safety of spillways while providing economic designs.

An analysis was performed on thirty-two (32) NRCS assisted dams with a high hazard classification. The dams were located in states east of the 105th meridian. The drainage areas of the structures varied from 0.41 to 156 square-miles. The average drainage area was 14.9 square-miles (excluding the 156 square mile site). The watershed time-of-concentration varied from 0.4 to 22 hours with an average of 3.85 hours. The 24-hour PMP ranged from 25 to 44 inches. Four rainfall distributions based on the World Curve were developed. The maximum rainfall intensity was centered at the 3rd, 6th, 9th and 12th hours. A SITES analysis was conducted on the 32 dams to determine the flow depths in the auxiliary spillways. The flow depths (Hp) in the auxiliary spillway increased for each structure as the center of the maximum one-hour moved from the 3rd hour to the 12th hour. The Hp values varied from 2.3 to 20.4 feet. The Hp from the 12th hour maximum intensity increased from 0.13 to 5.85 feet with an average increase of 1.75 feet compared to the 3rd hour maximum intensity.

An additional forty (40) NRCS assisted dams with a significant hazard classification were evaluated. The drainage areas of these structures varied from 0.17 to 82 square-miles. The average drainage area was 12.3 square-miles (excluding the 82 square mile site). The watershed time-of-concentration varied from 0.4 to 36 hours with an average of 3.92 hours. The 24-hour design rainfall volumes ranged from 8.31 to 23.72 inches. SITES analyses were conducted on these 40 dams using the four rainfall distributions based on the World Curve. The flow depths (Hp) in the auxiliary spillway increased for each structure as the center of the maximum one-hour moved from the 3^{rd} hour to the 12^{th} hour. The Hp values varied from 0 to 12.6 feet. The Hp from the 12^{th} hour maximum intensity increased from 0.13 to 4.36 feet with an average increase of 1.58 feet compared to the 3^{rd} hour maximum intensity.

Moving the center of the distribution to later hours increases the auxiliary spillway depth of flow and produces a more conservative reservoir design. It is easy to concede moving the center of the distribution to the 6^{th} hour since two of the historical storms in HMR-51 could have had their maximum intensities during the second six hours and it is desirable to have design criteria slightly on the conservative side. Centering the distribution on the 6^{th} hour is centering the maximum intensity in the middle of the maximum 12-hours, which accounts for 71 percent of the total rainfall. Placing the maximum one-hour at the 9^{th} hour puts the maximum intensity in the middle of the maximum 18-hours of precipitation, which accounts for 87 percent of total rainfall. Based on examination of the historical events in HMR-51, there appears to be no physical basis for centering the maximum intensity beyond the 9^{th} hour. Only five of the events had greater than 6-inches of rainfall between 6^{th} and 12^{th} hour and only three of the events had greater than 6-inches of rainfall between 12^{th} and 18^{th} hour. Placing the maximum one-hour intensity at either the 6^{th} or 9^{th} hour appears to be the reasonable and logical choice. The remainder of the design distribution can then be critically stacked on either side of the maximum one-hour value.

Figure 2 and Table 3 compares the proposed World Curve distribution with the other distributions discussed in this paper. Just as with the evaluation patterns discussed above, a key element of any suitable PMP design pattern is to get realistic maximum intensity values and hopefully get the higher intensity values in the proper sequence within the 24-hour event.

Comparison of 24-hour Distributions to 6-hour Distribution

Seventy-two (72) sites were evaluated with the SITES computer model. The 6-hour ESFB, 24-hour ESFB, 5-point, HMR-52 and the World Curve rainfall distributions were compared to determine the potential change in the height of the dams. In general terms, raising the dam height increases the construction costs. NRCS dams have been designed and constructed with the 6-hour design criteria for fifty years. Changing to 24-hour design criteria could have a significant effect on the cost of rehabilitating many of these structures.

The 24-hour ESFB rainfall distribution would require 25% of the dam heights to increase with 72% within plus or minus one foot of the 6-hour ESFB design criteria. The 5-point rainfall distribution would require 54% of the dam heights to increase with 61% within plus or minus one foot of the 6-hour ESFB design criteria. The HMR-52 rainfall distribution would require 97% of the dam heights to increase with 47% within plus or minus one foot of the 6-hour ESFB design criteria. The World Curve rainfall distribution with the maximum intensity at the 6th hour would require 8% of the dam heights to increase with 22% within plus or minus one foot of the 6-hour ESFB design criteria. The World Curve rainfall distribution with the maximum intensity at the 9th hour would require 14% of the dam heights to increase with 54% within plus or minus one foot of the 6-hour ESFB design criteria.

The comparison of the SITES analysis is included in Table 4. The 24-hour World Curve distribution with maximum intensity at either the 6th or 9th hour, if adopted, would have the least effect on the required dam height for the sites in the study.

Conclusions

The applicability of the critically stacked World Curve Distribution to the area east of the 105th Meridian was evaluated. The World Curve Distribution was found to be either valid or at least worthy of further consideration. The World Curve Distribution is a valid basis for design of high hazard structures.

The 24-hour World Curve Distribution is greater than the current 24-hour ESFB pattern for the maximum one-hour intensity. For all other volume-durations, the 24-hour World Curve Distribution is less than the 24-hour ESFB pattern. The World Curve is a critically stacked pattern that should not be exceeded for any regional distribution that essentially parallels the World Curve distribution. Overall, the two curves are remarkably similar considering that they were developed from two entirely different sources. The overwhelming difference is that the 24-hour World Curve was developed from PMP size events while the 24-hour ESFB distribution was developed from four-inch to ten-inch size events and then extrapolated to larger events. It would seem logical to use the World Curve distribution for PMP size events. The fact that the two curves are very similar comes as a surprise. The areas of the US where this distribution applies will be discussed in a companion paper.

The HMR-52 distribution would be the most conservative design and the World Curve distribution would be the least conservative design compared to the present NRCS 6-hour ESFB design for significant and high hazard dams. The HMR-52 distribution would require increasing the dam design height of 97% of the study sites. The 5-point distribution would require increasing the dam design height of 54% of the study sites. The 24-hour ESFB distribution would require increasing the dam design height of 25% of the study sites. The World Curve distribution centered at the 9th hour would require increasing the dam design height of 14% of the study sites. The World Curve distribution centered at the 6th hour would require increasing the dam design height of 8% of the study sites.

A resultant rainfall distribution developed from the World Curve data with the maximum one-hour intensity centered at the 6th or 9th hour will give a comfortably conservative design for all NRCS high and significant hazard dams located east of the 105th Meridian.

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Table 1: Maximum Observed World-wide Point Rainfall

Duration, hour	Rainfall, inches	Location	Dates
0.50	11.02	Sikeshugou, Hebei, China	July 3, 1974
0.70	12.00	Holt, MO, USA	June 22, 1947
1.00	15.78	Shangdi, Inner Mongolia, China	July 3, 1975
1.20	17.32	Gaoj, Gansu, China	August 12, 1985
2.00	19.25	Yujiawanzi, Inner Mongolia, China	July 19, 1975
2.50	21.65	Bainaoboa, Hebei, China	June 25, 1972
2.75	22.00	D'Hanis, TX, USA	May 31, 1935
3.00	23.62	Duan Jiazhuang, Hebei, China	June 28, 1973
4.50	30.80	Smethport, PA, USA	July 18, 1942
6.00	33.07	Muduocaidang, Inner Mongolia, China	August 1, 1977
10.00	55.12	Muduocaidang, Inner Mongolia, China	August 1, 1978
18.00	62.56	Foc Foc, Reunion	January 7-8, 1966
20.00	66.81	Foc Foc, Reunion	January 7-8, 1967
22.00	70.08	Foc Foc, Reunion	January 7-8, 1968
24.00	71.85	Foc Foc, Reunion	January 7-8, 1969
48.00	97.12	Aurere, Reunion	April 8-10, 1958
72.00	127.56	Grand Ilet, Reunion	January 24-27, 1980
96.00	146.50	Cherrapunji, India	September 12-15, 1974
120.00	155.55	Commerson, Reunion	January 23-27, 1980
144.00	169.41	Commerson, Reunion	January 22-27, 1980
168.00	183.19	Commerson, Reunion	January 21-27, 1980
192.00	194.33	Commerson, Reunion	January 20-27, 1980
216.00	210.31	Commerson, Reunion	January 19-27, 1980
240.00	223.53	Commerson, Reunion	January 18-27, 1980
264.00	234.21	Commerson, Reunion	January 17-27, 1980
288.00	238.23	Commerson, Reunion	January 16-27, 1980
312.00	239.06	Commerson, Reunion	January 15-27, 1980
336.00	239.45	Commerson, Reunion	January 15-28, 1980
360.00	239.49	Commerson, Reunion	January 14-28, 1980
744.00	366.14	Cherrapunji, India	July 1-31, 1861
1464.00	502.63	Cherrapunji, India	June - July, 1861

Table 2: Maximum Observed US Point Rainfall

NCDC State Code	State ID	Site ID	Year	Month	Day	1 hour	Name	Lat.	Long.
01	AL	6942	1973	4	26	6.2	RIVER FALLS 2 NE	3122	8631
02	AZ	0775	1986	7	14	4.8	BIG DIPPER DAIRY	6033	15053
03	AR	2978	1977	8	12	5.6	GREERS FERRY DAM	3531	9200
04	CA	6657	1992	8	13	5.4	PALOMAR MOUNTAIN OBSV	3321	11652
05	CO	4538	1998	9	30	5.6	KIM 15 NNE	3727	10319
06	CT	9388	1973	9	6	4.2	WEST THOMPSON LAKE	4157	7154
07	DE	6410	1984	7	21	3.4	NEWARK UNIVERSITY FARM	3940	7544
08	FL	0845	1992	11	18	6.4	BOCA RATON	2622	8007
09	GA	3460	1992	8	5	6.4	FOLKSTON 3 SW	3048	8202
10	ID	5708	1984	7	27	2.8	MCCALL	4454	11607
11	IL	2417	1986	9	19	4.8	DOWNS 2 NE	4026	8852
12	IN	7125	1973	5	28	6.4	PRINCETON 1 W	3821	8735
13	IA*	5769	1986	8	12	8 (6.6)	MOUNT AYR 4 SW	4041	9418
14	KS	7420	1971	7	28	6.6	No Records	3898	9472
15	KY	6096	1972	9	10	6.4	OWENSBORO TRTMNT PLT E	3746	8705
16	LA	2971	1973	4	3	6.4	EPPS 6 WNW	3237	9134
17	ME	6435	1996	6	14	4.6	No Records	4488	6867
18	MD	0700	1975	6	26	5.2	BELTSVILLE	3902	7653
19	MA	0840	1990	7	24	4.4	No Records	4195	7095
20	MI	0735	1988	9	3	4	BERRIEN SPRINGS 5 W	4157	8625
21	MN	1263	1994	7	15	5.8	CANBY	4443	9617
22	MS	7220	1991	10	23	7	PURVIS	3109	8924
23	MO	5987	1996	7	8	5.6	NEVADA SEWAGE PLANT	3751	9424
24	MT	3581	1989	8	30	4.8	GLENDIVE	4706	10443
25	NE	6386	1972	7	1	7	No Records	4150	10225
26	NV	2557	1988	7	30	3.8	ELGIN	3721	11433
27	NH	0741	1972	7	19	4.4	BLACKWATER DAM	4319	7143
28	NJ	8880	1987	7	2	4.2	No Records	4027	7478
29	NM	4112	1992	6	7	5.4	HOPE	3249	10444
30	NY	5512	1978	10	26	5.6	MORRISVILLE 3 S	4251	7539
31	NC	4860	1993	9	5	6.6	LAURINBURG	3445	7927
32	ND	0492	1977	7	10	5.2	BALFOUR 6 SSW	4753	10033
33	OH	4686	1971	9	6	4.6	No Records	3988	8343
34	OK	6935	1996	8	17	7	PAWHUSKA	3640	9621
35	OR	1828	1983	7	20	3.4	No Records	4208	12310
36	PA	2537	1995	6	25	6	EISENHOUER NAT HIST	3948	7716
37	RI	5215	1983	8	11	3.2	NEWPORT WATER WORKS	4131	7119
38	SC	5017	1978	7	31	7	LAURENS	3430	8202
39	SD	1076	1977	6	15	5.2	BROOKINGS 2 NE	4419	9646
40	TN	6170	1999	8	24	6	MONTEREY	3608	8515
41	TX	9829	1986	8	25	7.4	No Records	3177	10315
42	UT	7959	1974	7	20	3.6	SOLDIER SUMMIT	3956	11105
43	VT	4882	1984	8	29	3.6	MANCHESTER	4310	7304
44	VA	5851	1986	5	1	6	MOUNT WEATHER	3904	7753
45	WA	0013	1982	5	28	3.6	ABERDEEN 20 NNE WISHKA	4716	12342
46	WV	6163	1981	9	1	5.4	MOOREFIELD 2 SSE	3902	7858
47	WI	2447	1985	8	12	5.4	EAU PLEINE	4444	8945
48	WY	4910	1986	3	6	3.6	JACKSON	4329	11046

* Second highest hourly rainfall for Iowa shown in parenthesis.

Table 3: Distribution Comparison

Duration, hour	Rainfall Distribution			
	World Curve	ESFB	HMR-52	5-Point
0	0.0%	0.0%	0.0%	0.0%
1	21.6%	19.2%	1.2%	1.5%
2	30.1%	35.3%	2.4%	3.0%
3	36.6%	43.3%	3.7%	4.5%
4	42.1%	48.7%	5.2%	5.9%
6	51.2%	57.4%	8.6%	8.9%
9	62.3%	67.4%	28.4%	42.9%
12	71.5%	75.8%	77.6%	76.9%
15	79.7%	82.9%	87.2%	84.0%
18	87.0%	89.2%	94.2%	91.1%
21	93.8%	94.8%	97.3%	95.5%
24	100.0%	100.0%	100.0%	100.0%

Table 4: Effect on Dam Height by Rainfall Distribution Compared to NRCS 6-hour Design Criteria

Effect on Dam Height	ESFB		5 Point		HMR-52		World Curve Max at 6th hour		World Curve Max at 9th hour	
	No.	%	No.	%	No.	%	No.	%	No.	%
High Hazard Dams										
Raise Dam more than 1 foot	2	6.3%	5	15.6%	18	56.3%	2	6.3%	2	6.3%
Raise Dam less than 1 foot	2	6.3%	8	25.0%	12	37.5%	0	0.0%	1	3.1%
Lower Dam less than 1 foot	13	40.6%	4	12.5%	2	6.3%	2	6.3%	5	15.6%
Lower Dam between 1 and 2 feet	10	31.3%	6	18.8%	0	0.0%	12	37.5%	14	43.8%
Lower Dam more than 2 feet	5	15.6%	9	28.1%	0	0.0%	16	50.0%	10	31.3%
Significant Dams										
Raise Dam more than 1 foot	1	2.5%	5	12.5%	20	50.0%	0	0.0%	0	0.0%
Raise Dam less than 1 foot	13	32.5%	21	52.5%	20	50.0%	4	10.0%	7	17.5%
Lower Dam less than 1 foot	24	60.0%	11	27.5%	0	0.0%	10	25.0%	26	65.0%
Lower Dam between 1 and 2 feet	1	2.5%	2	5.0%	0	0.0%	24	60.0%	6	15.0%
Lower Dam more than 2 feet	1	2.5%	1	2.5%	0	0.0%	2	5.0%	1	2.5%

Figure 1: World-wide Maximum Point Rainfall - Duration

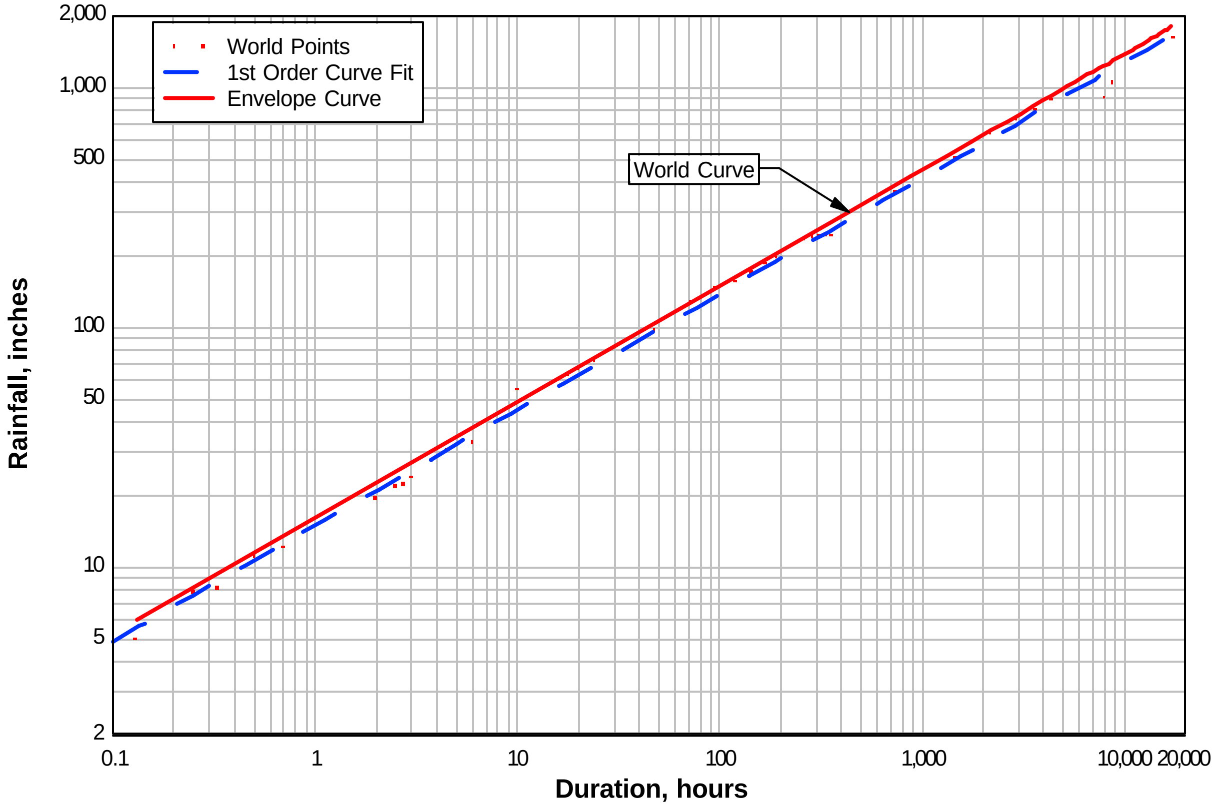

Figure 2: Rainfall Distribution Comparison